Muon Collider Physics

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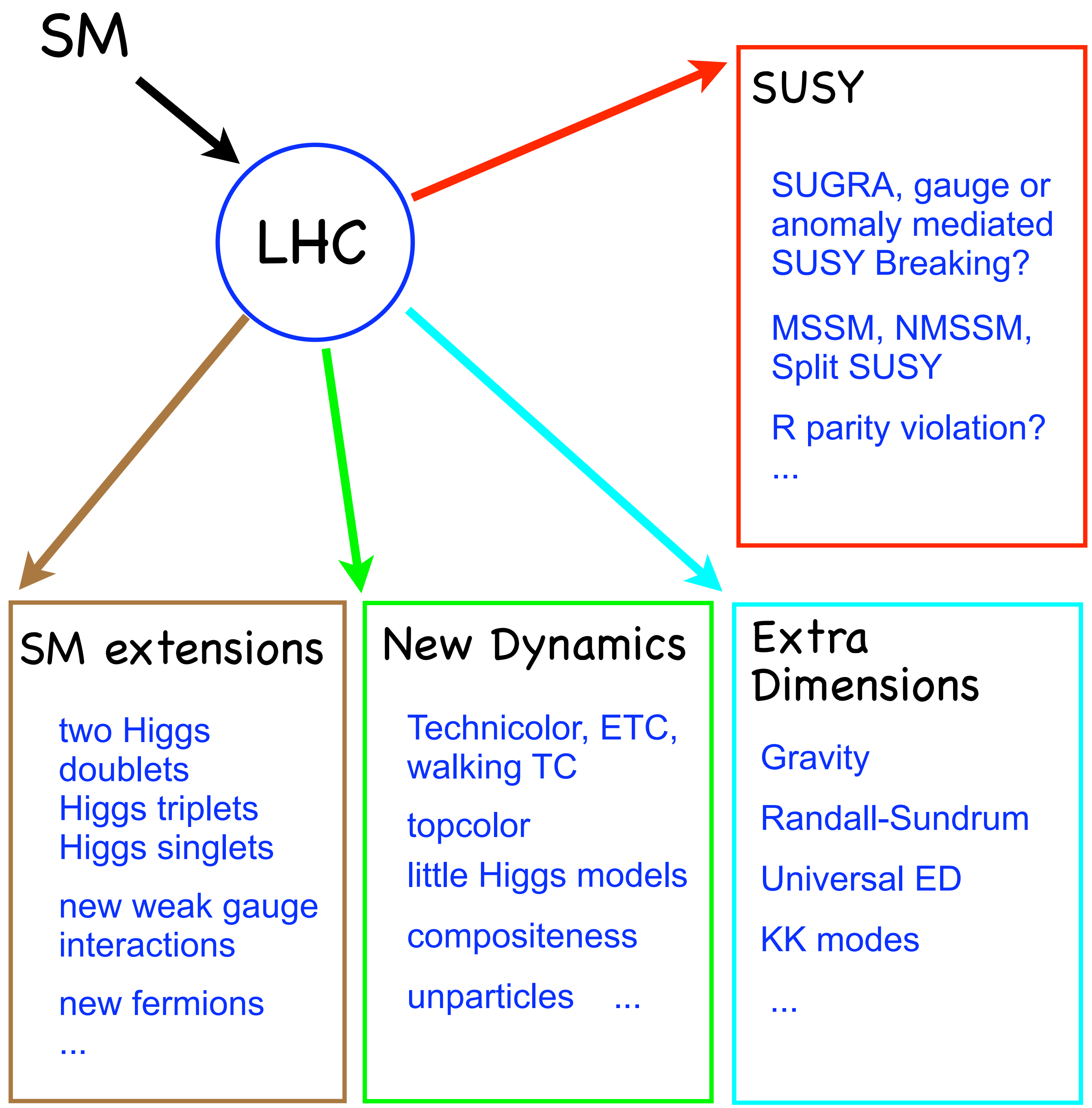
Fermilab

Crossroad In Theoretical Physics

- Existing facilities in 2020:
  - LHC with luminosity or energy upgrade
- Options:
  - low energy lepton collider:
    ILC (500 GeV) (upgradable) or
    muon collider - Higgs Factory
  - lepton collider in the multi Tev range:
    CLIC or muon collider
  - hadron collider in hundred TeV range:
    VLHC
- High energy lepton collider likely required for full study of Terascale physics.



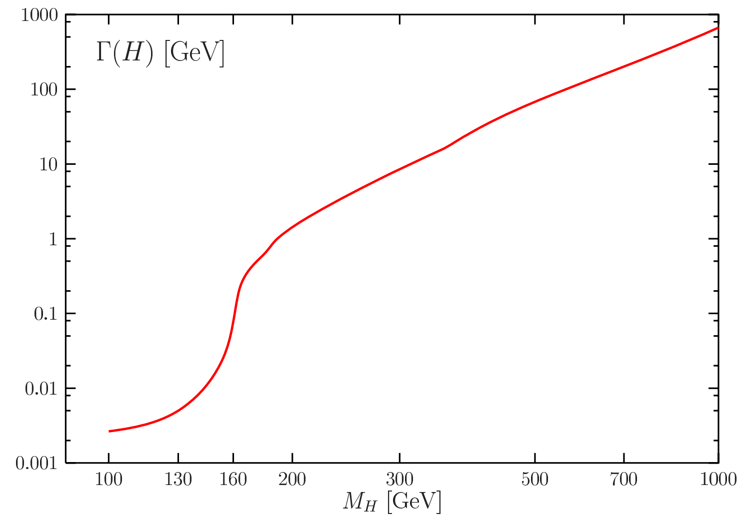
Basics ($\sqrt{s}$ < 500 GeV)

- For $\sqrt{s}$ < 500 GeV lepton collider
  - SM threshold regions:
    top pairs; W^+W^-; Z^0Z^0; Z^0h production
- For low energy muon collider
  - s-channel Higgs production
    - Coupling $\propto$ lepton mass

$$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$$

    - Narrow width

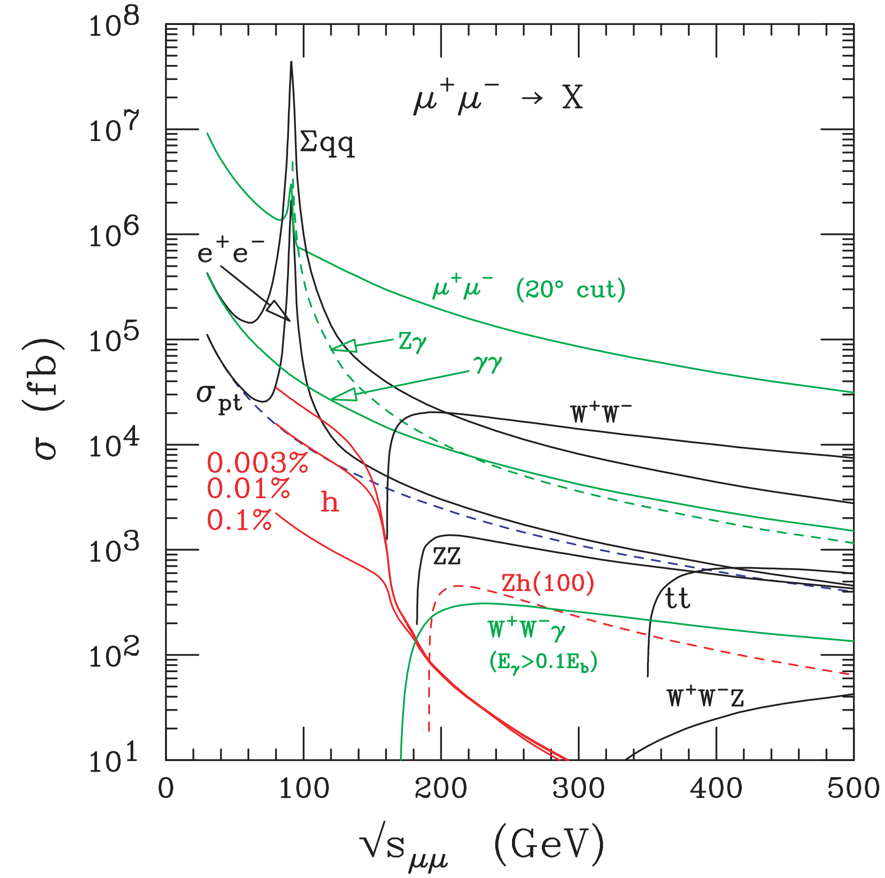
$$\begin{aligned} \Gamma &= 3.6 \text{ MeV} \\ (m_h &= 120 \text{ GeV}) \end{aligned}$$

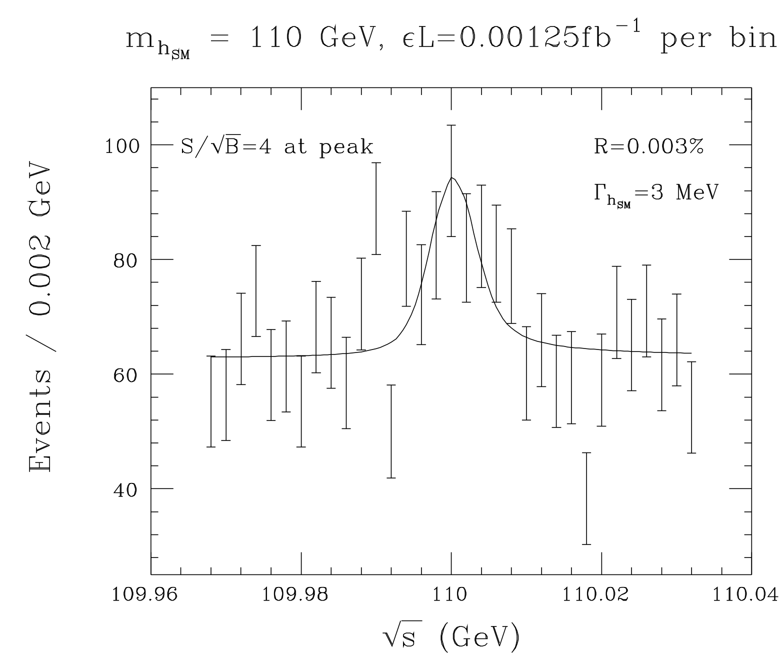


    - Direct width measurement

$$\Delta E/E \approx 0.003\% \quad \text{and } 100\ pb^{-1}$$

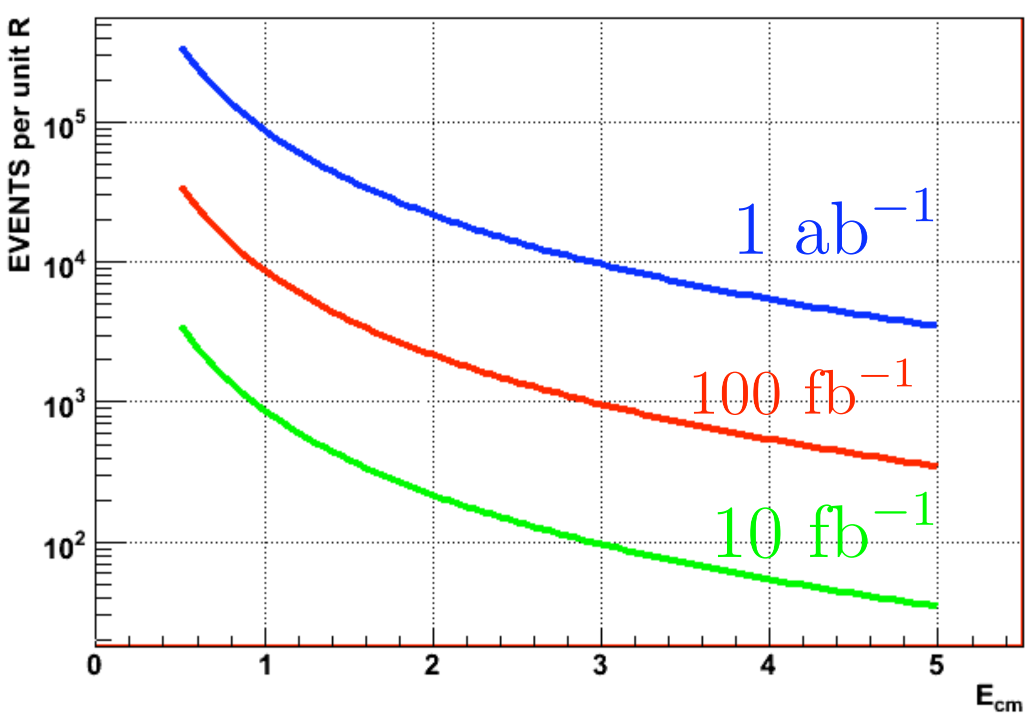
Standard Model Cross Sections





Basics ($\sqrt{s}$ > 500 GeV)

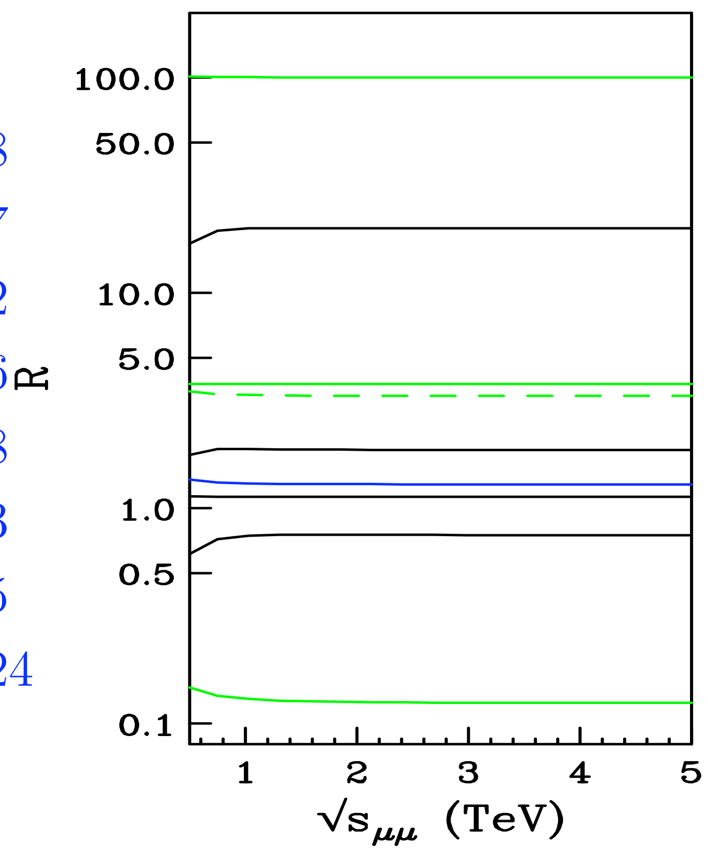
- For $\sqrt{s}$ > 500 GeV
  - Above SM pair production thresholds: R ≡ σ/σ_{QED} ($\mu^+\mu^-$->e+e-)   flat
- Luminosity Requirements



R at $\sqrt{s}$ = 3 TeV

$O(\alpha_{em}{}^2)$ $O(\alpha_s{}^0)$

$$\begin{aligned}
\mu^+\mu^-(20^o\ \mathrm{cut}) &= 100 \\
W^+W^- &= 19.8 \\
\gamma\gamma &= 3.77 \\
Z\gamma &= 3.32 \\
t\bar{t} &= 1.86 \\
b\bar{b} &= 1.28 \\
e^+e^- &= 1.13 \\
ZZ &= 0.75 \\
Zh(120) &= 0.124
\end{aligned}$$



(one unit of R)

$$\sigma_{\mathrm{QED}}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \mathrm{fb}}{s(\mathrm{TeV}^2)}$$

For example: $\sqrt{s} = 3.0\ \mathrm{TeV}$ $\Rightarrow$ 965 events/unit of R

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}$$
$$\to 100\ \mathrm{fb}^{-1}\mathrm{year}^{-1}$$

Processes with R ≥ 0.1 can be studied

Total - 128 K SM events per year

Minimum Luminosity for Muon Collider

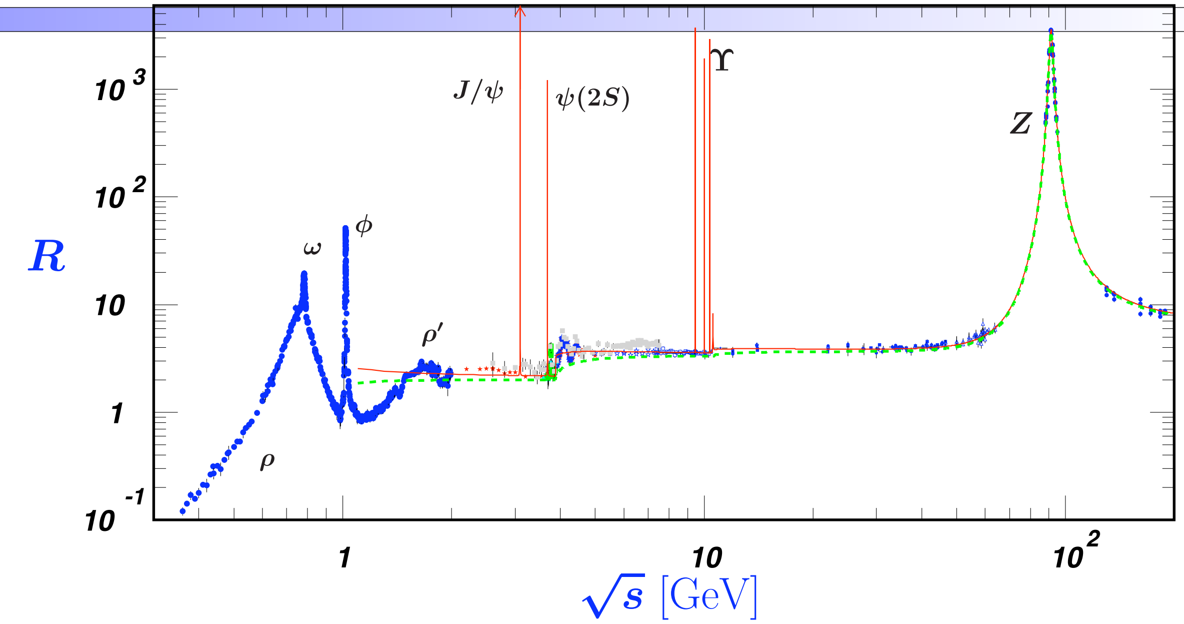
- Universal behavior for s-channel resonance

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2 + \Gamma^2/4} \right] B_{in} B_{out}$$

Convolute with beam resolution ΔE.

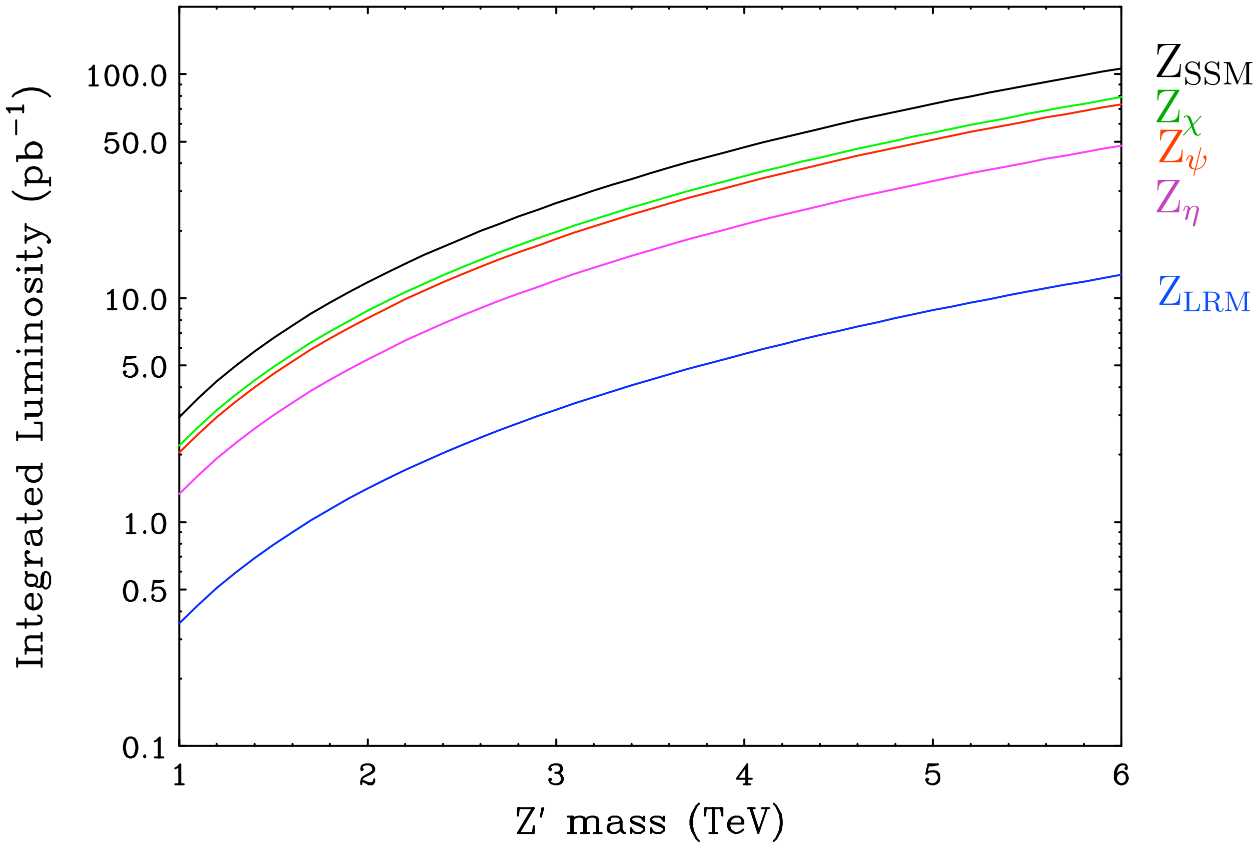
If ΔE« Γ

$$\boxed{R_{\text{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-) B(visible)}{\alpha_{\text{EM}}^2}}$$



- Can use to set minimum required luminosity
  - Likely new physics candidates:
    - scalars: h, H^0, A^0,...
    - gauge bosons: Z′
    - new dynamics: bound states
    - ED: KK modes
  - Example - new gauge boson: Z′
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

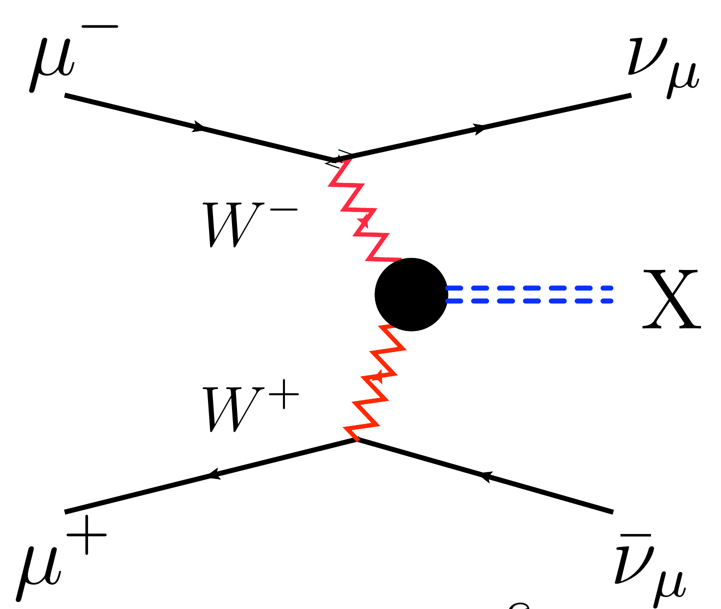
Minimum luminosity at Z′ peak:
$\mathcal{L}$ = 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}
for M(Z′) -> 1.5-5.0 TeV



The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak

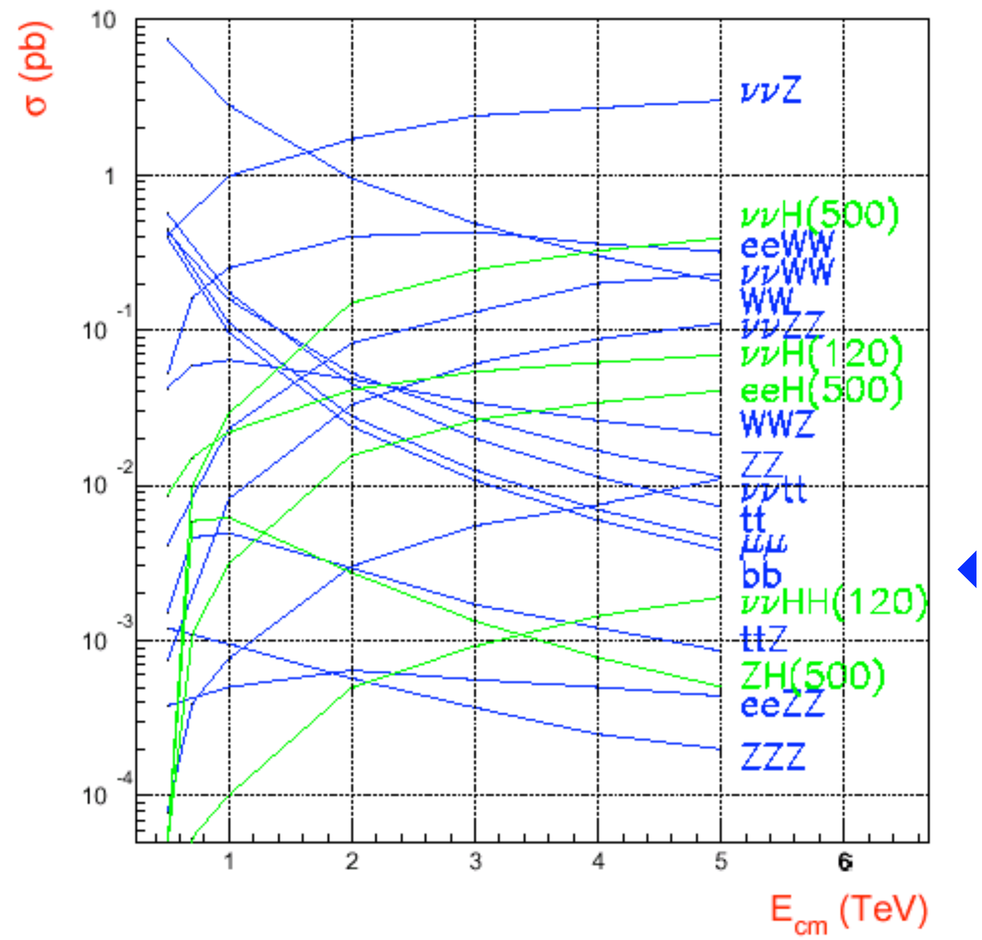
Fusion Processes

- Important at multi Tev energies
- Large cross sections
- Increase with s.
- $M_X^2 < s$



$$\sigma(s) = C\ln(\frac{s}{M_X^2}) + \ldots$$

CLIC (or MC e<->μ)



X	R (@ 3 TeV)
Z^0	230
$h^0(500)$	25
W^+W^-	19.8
Z^0Z^0	5.8
$h^0(120)$	5.5
$t\bar{t}$	0.6
$h^0h^0(120)$	0.1

- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cuts

Studying the Higgs Boson

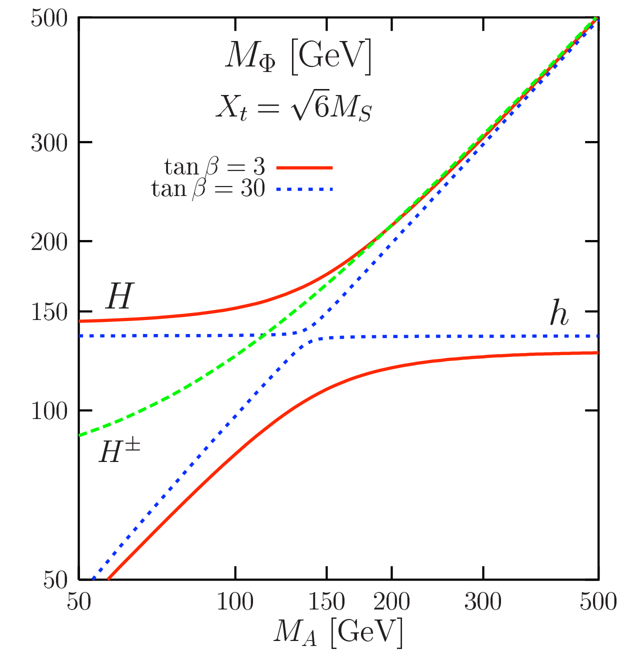
- Various processes available for studying the Higgs at a muon collider:
  - s-channel direct production: h^0 ($\sqrt{s} = m_h$) — only MC
  - associated production: Zh^0 — MC or CLIC
    - R ~ 0.12
    - search for invisible h^0 decays
  - Higgsstrahlung: $t\bar{t}h^0$ — MC or CLIC: needs 10 ab^{-1} !!
    - R ~ 0.01
    - measure top coupling
  - W*W* fusion : $\nu_\mu \bar{\nu}_\mu h^0$ — MC or CLIC: good benchmark process
    - R ~ 1.1 s ln(s) (s in TeV^2) (m_h = 120 GeV)
    - study some rare decay modes
    - measure Higgs self coupling

Two Higgs Doublets (MSSM)

- decay amplitudes depend on two parameters:

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\tan 2\beta.$$



- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings to top quarks suppressed by $1/\tan\beta$ factor.

- good energy resolution is needed for H^0 and A^0 studies:

good benchmark process

- for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
- nearby in mass need good energy resolution to separate H and A.
- can use bremsstrahlung tail to see states using bb decay mode.

New Fermions and Gauge Bosons

- Present CDF/D0 bounds on W′, Z′, and new quarks effectively rule out production at ILC(500).

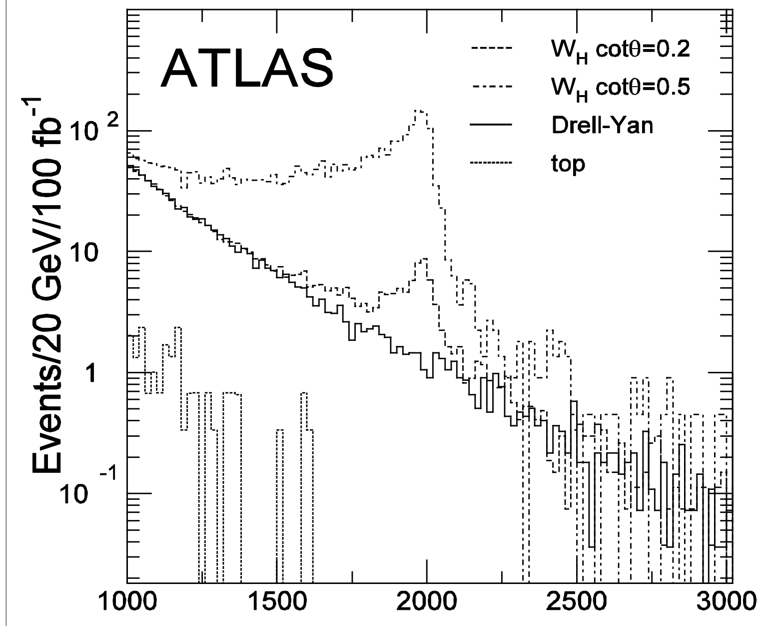
State	CDF/D0 Limit (GeV)
Quark: (W,Z,h) + jet	325
Z′ (SM)	923
W′ (SM)	860

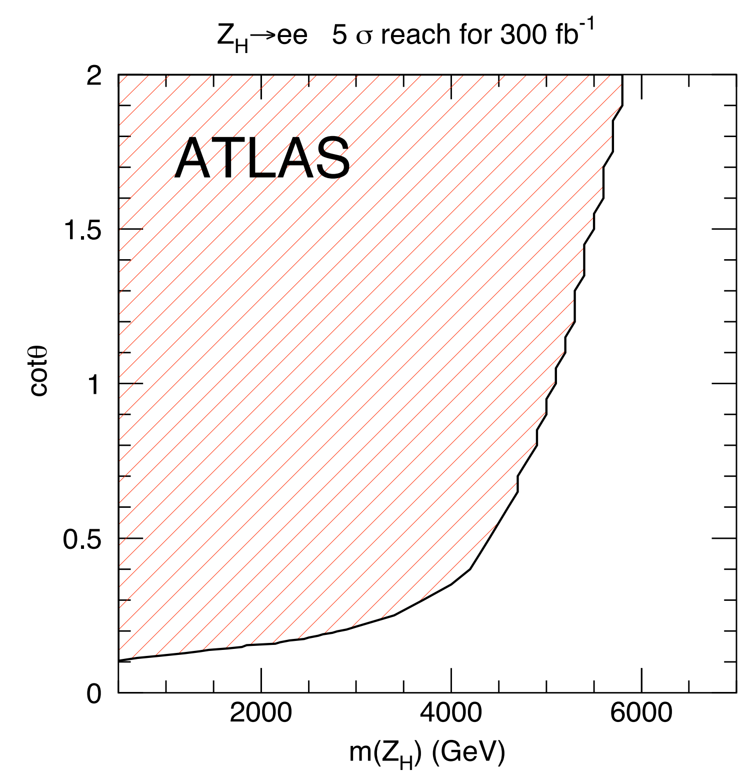
- Littlest Higgs Model: good benchmark processes
  charge (2/3) quark T (EW singlet),
  new W, Z, and A gauge bosons, Higgs triplet

  At the LHC, T observable for m(T) < 2.5 TeV
  For W, Z, and A dependent on mixing parameters

- Muon collider will allow detailed study.
  Requires high luminosity 1 ab^{-1} for T

ATLAS study LHC [hep-ph/0402037]





SUSY Studies

- Many studies of constraints on cMSSM
  - Direct limits (LEP, CDF, Dzero): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
  - Electroweak precision observables (EWPO): $M_W^2, \sin^2\theta_{sw}, (g-2)_\mu, \ldots$
  - B physics observables (BPO): $b \to s + \gamma,\ \mathrm{BR}(B_s \to \mu^+\mu^-), \ldots$
  - Cold dark matter (CDM): $\Omega_{DM} = .23 \pm .04$

J. Ellis, S. Heinemeyer, K.A. Olive, A.M. Weber, G. Wieglein [arXiv:0706.0652] ;
D. Feldman, Zuowei Lui and Pran Nath, PRL 99, 251802 (07); [arXiv:0802.4085] ; ...

- Full coverage likely requires a multi TeV lepton collider

S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]
(using only EWPO, BPO and LEP)

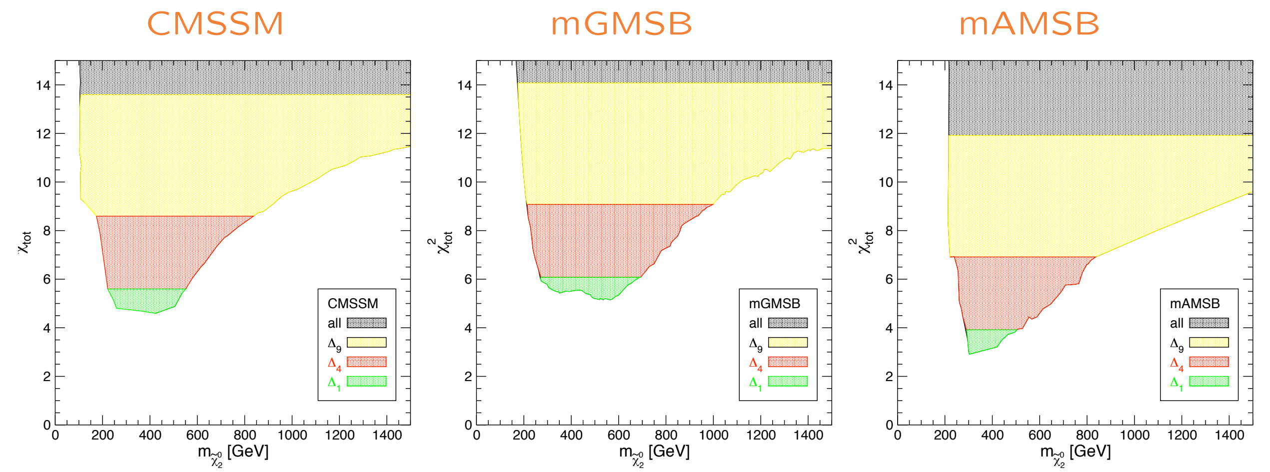
Second lightest neutralino:

m($\tilde{\chi}_2$) < 900 GeV for $\Delta\chi^2 < 4$

Heavy for LHC - possibly in decay chain ?

Lepton collider: $\chi_2^0 \to \chi_1^0 + X$

Second lightest neutralino



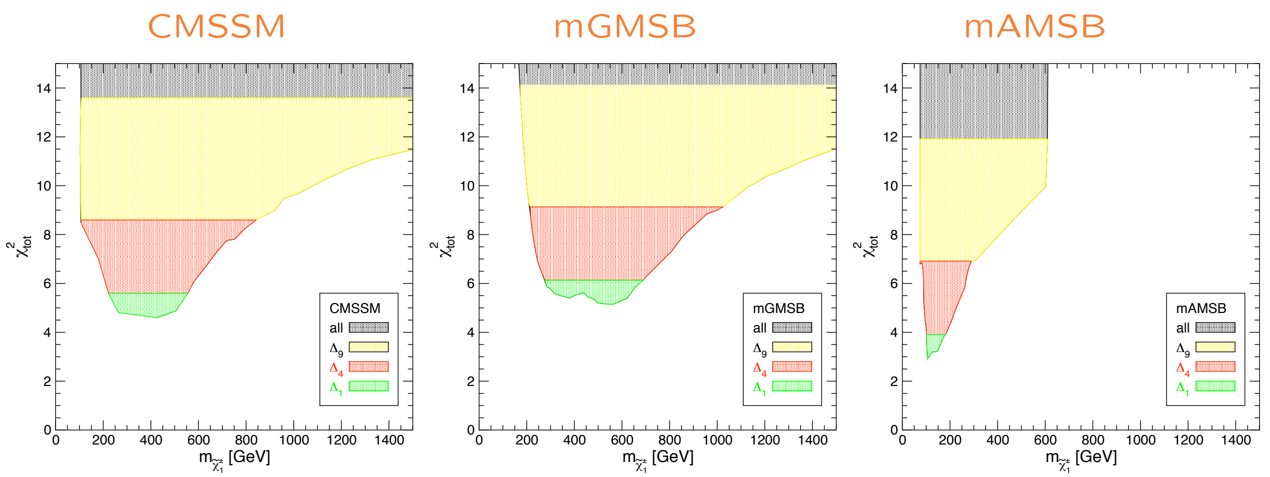
Lightest chargino:

m($\tilde{\chi}_1^+$) < 800, 900, 300 GeV for $\Delta\chi^2 < 4$

Heavy for LHC - possibly in decay chain ?

Lepton collider: Observable at ILC for mAMSB

Lightest chargino



Lightest stop, sbottom and gluino:

m($\tilde{t}_1$) > 500 for $\Delta\chi^2 < 4$

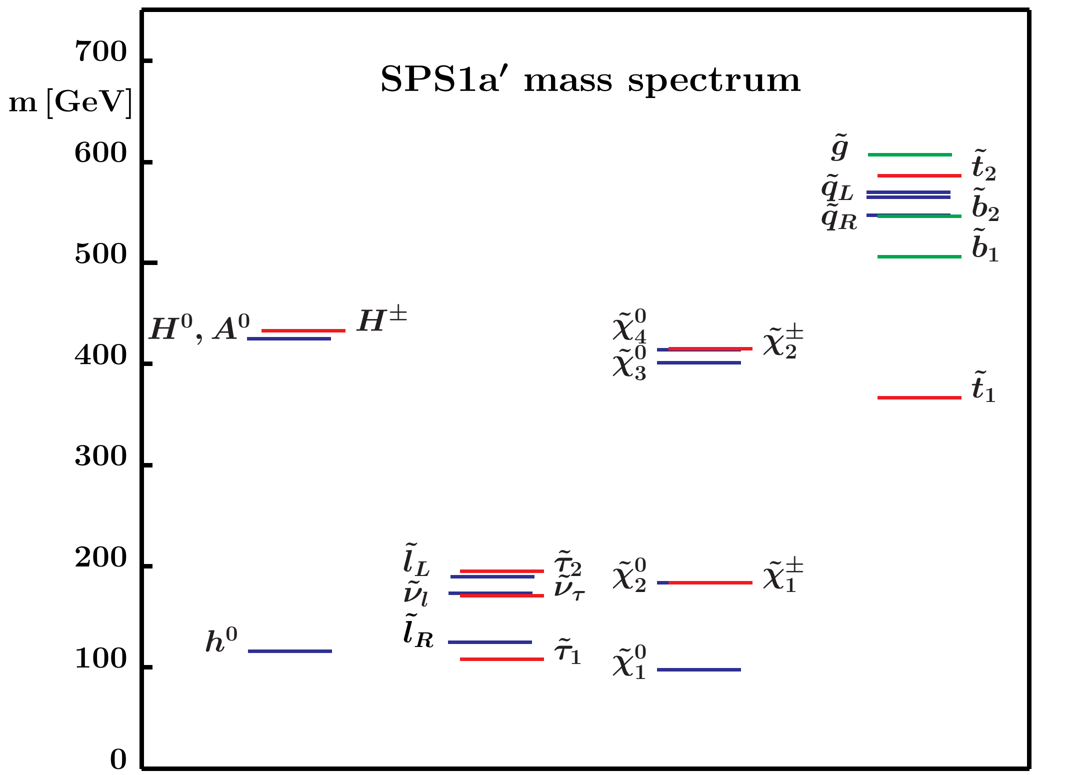
Easy for LHC up to 2 TeV

Lepton collider: Detailed study?

Modifying cMSSM

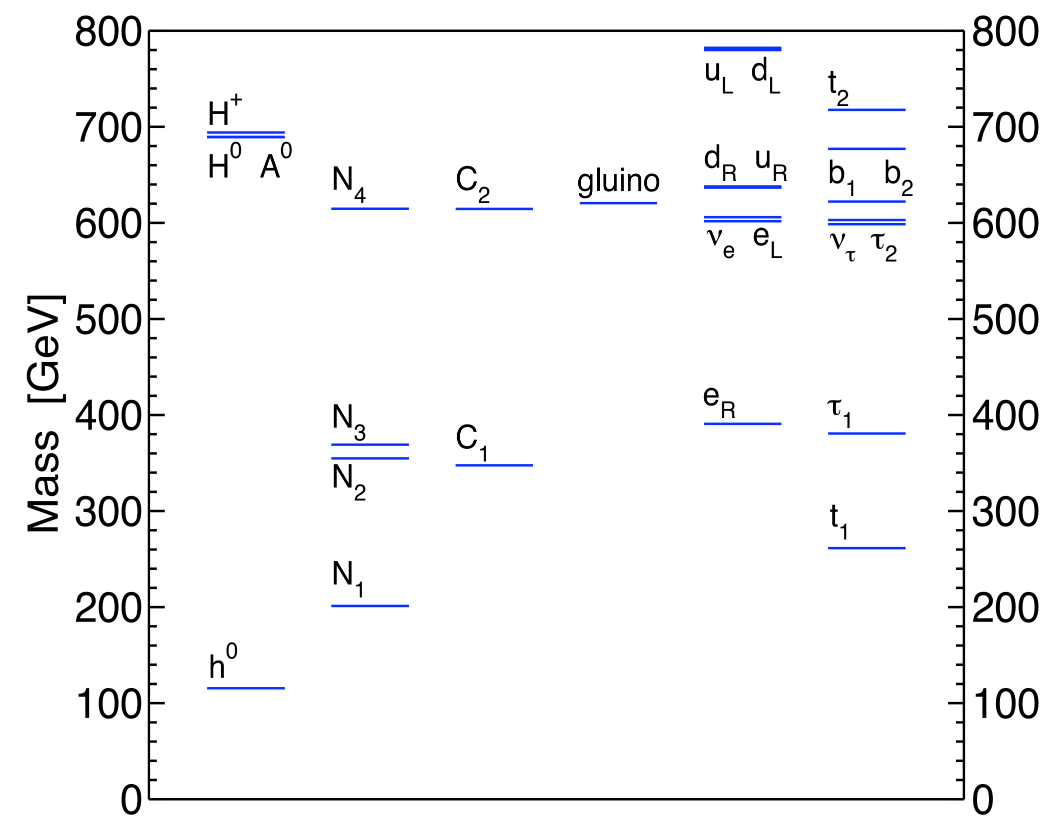
- Fine tuning problems in the cMSSM - Allow non universal $m_{1/2}$

cMSSM ILC Benchmark



Compressed SUSY

S. Martin [PR D75:115005,2007]



Many visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.2 TeV.

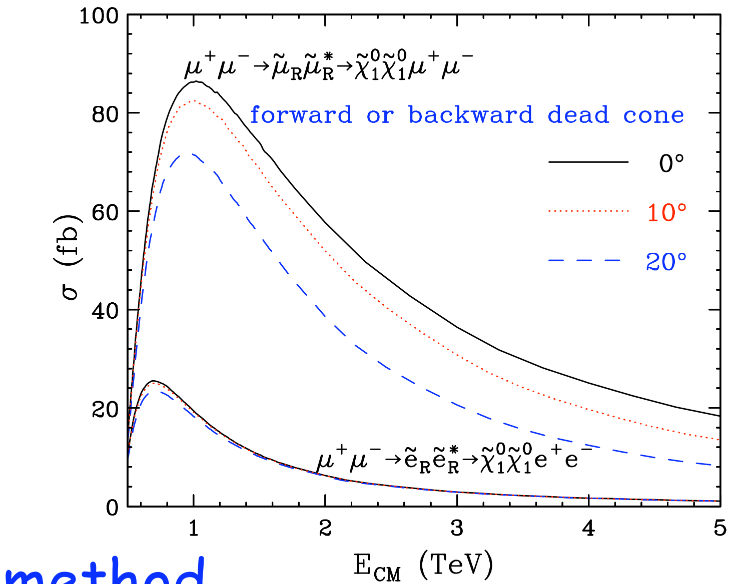
No visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.6 TeV.

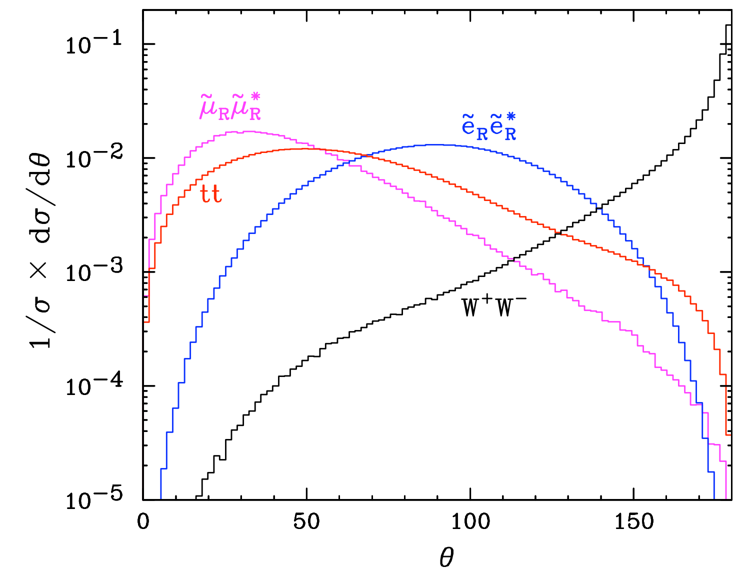
Supersymmetry provides strong case for a multi-TeV lepton collider

Example Process at Muon Collider

$$\mu^+\mu^- \to \tilde{e}_1^+\tilde{e}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$$

- Angular cut at 20°:
  50% reduction for smuon pair,
  20% reduction for selectron pair





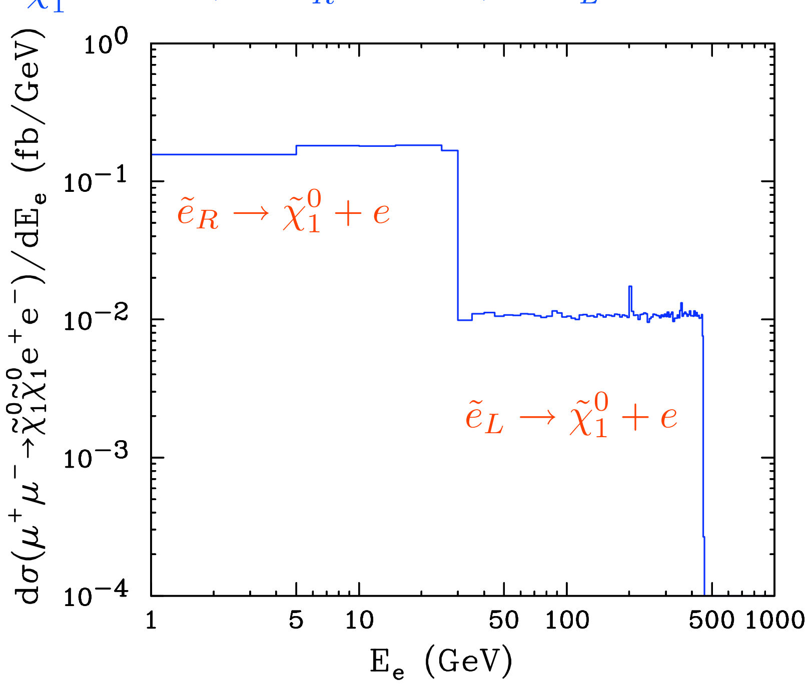
- Mass measurements using edge method better for MC than CLIC:

$$E_{\max/\min} = \frac{1}{2}M_{\tilde{e}}\left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{e}}}\right]\gamma(1\pm\beta)$$

Effect of beamstrahlung

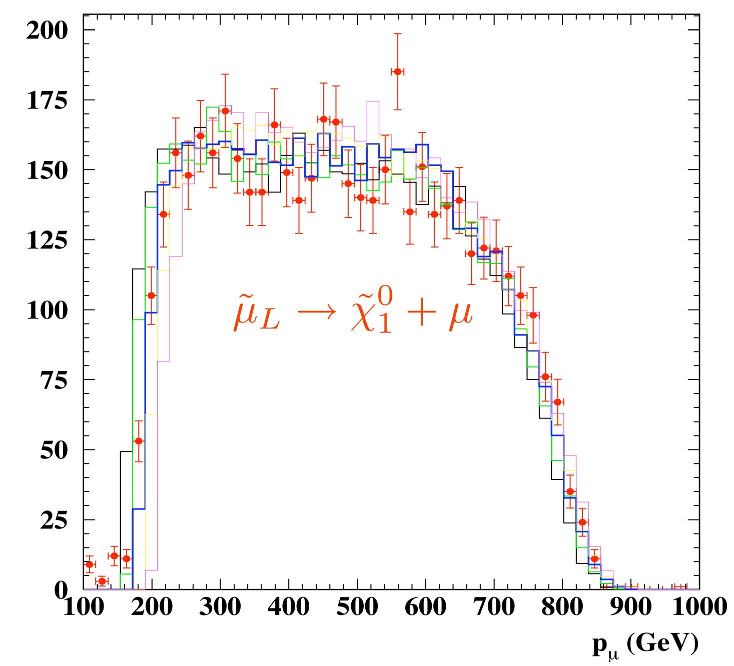
Kong, Winter (MC)

$m_{\tilde{\chi}_1^0} = 212;\ m_{\tilde{e}_R} = 222;\ m_{\tilde{e}_L} = 374$ GeV

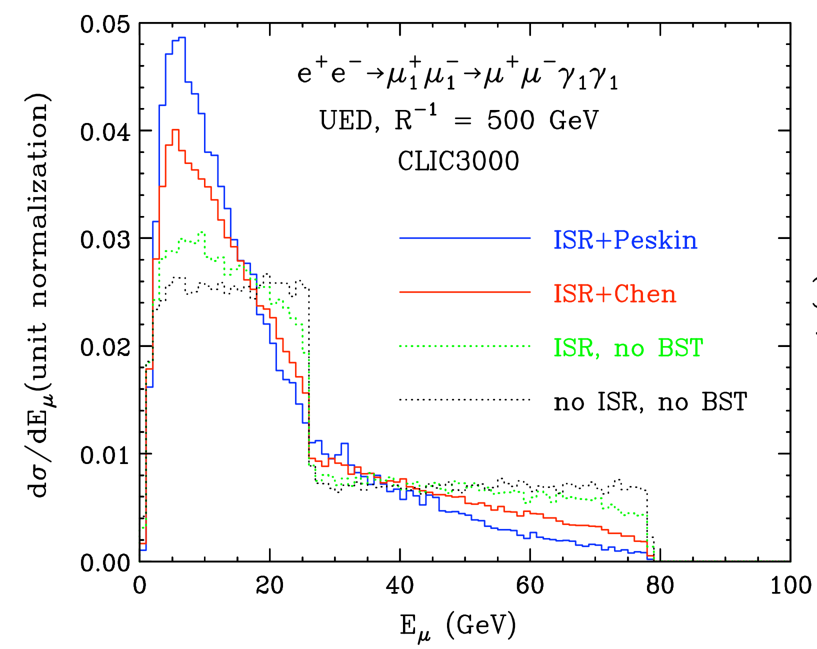


CLIC report (2004)

$m_{\tilde{\chi}_1^0} = 660$ GeV; $m_{\tilde{\mu}_L} = 1150$ GeV



Datta, Kong and Matchev
[arXiv:hep-ph/0508161]



New Strong Dynamics

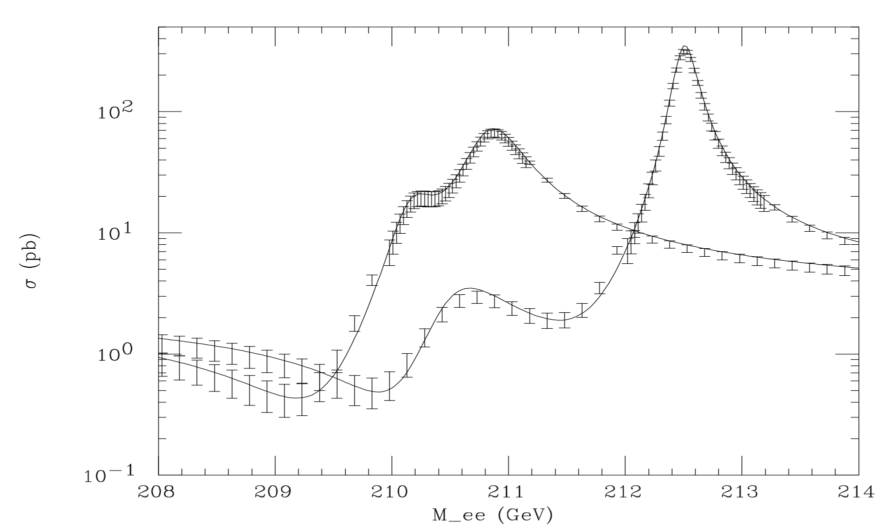
Theoretical issues

- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

Technicolor, ETC, Walking TC, Topcolor , ...

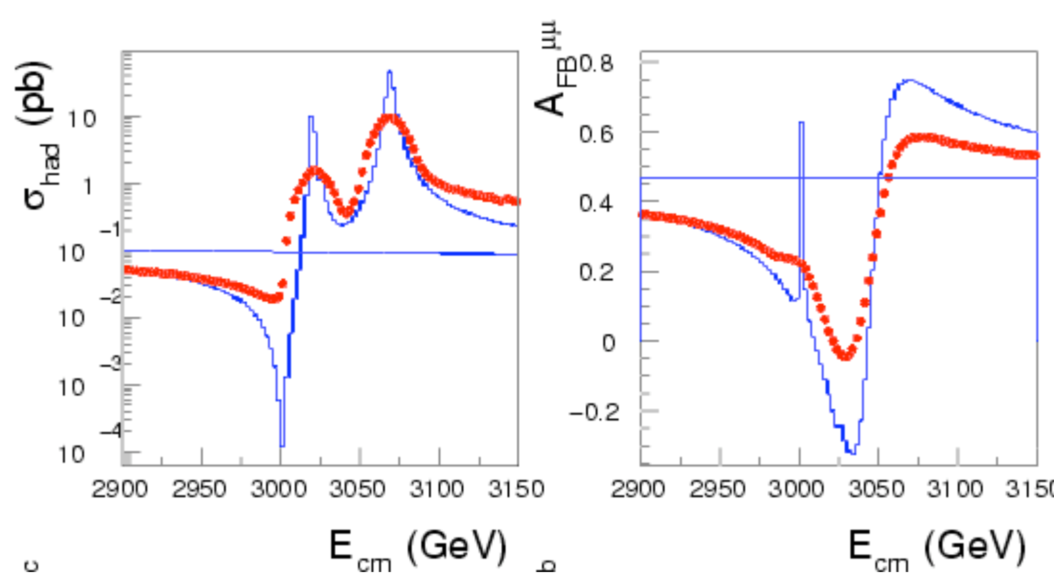
- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances - need fine energy resolution of muon collider.

Eichten, Lane, Womersley PRL 80, 5489 (1998)
$M(\rho_T)$ = 210 GeV $M(\omega_T)$ = 211, 209 GeV
MC 40 steps (total 1 fb^{-1})



good benchmark processes

CLIC - D-BESS model (resolution 13 GeV)



Contact Interactions

- New interactions (at scales not directly accessible) give rise to contact interactions.

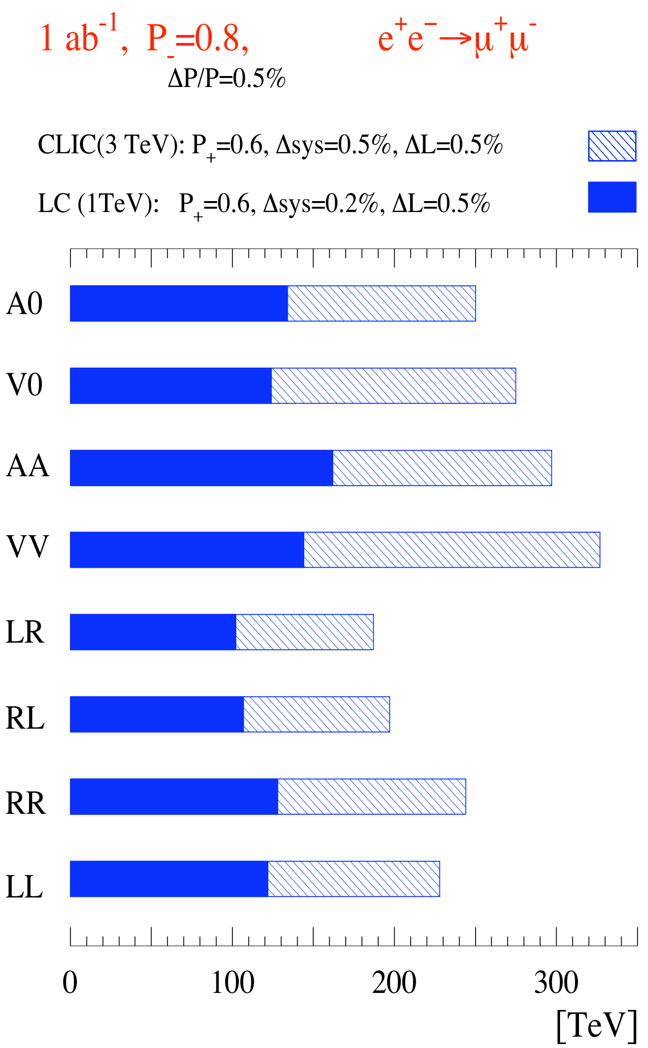
$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

Muon Collider Study
E.Eichten, S.~Keller, [arXiv:hep-ph/9801258]

- Muon collider is sensitive to contact interaction scales over 200 TeV as is CLIC.
- Cuts on forward angles for a muon collider not an issue.
- Polarization useful to disentangle the chiral structure of the interaction. (CLIC)

good benchmark process

CLIC Study

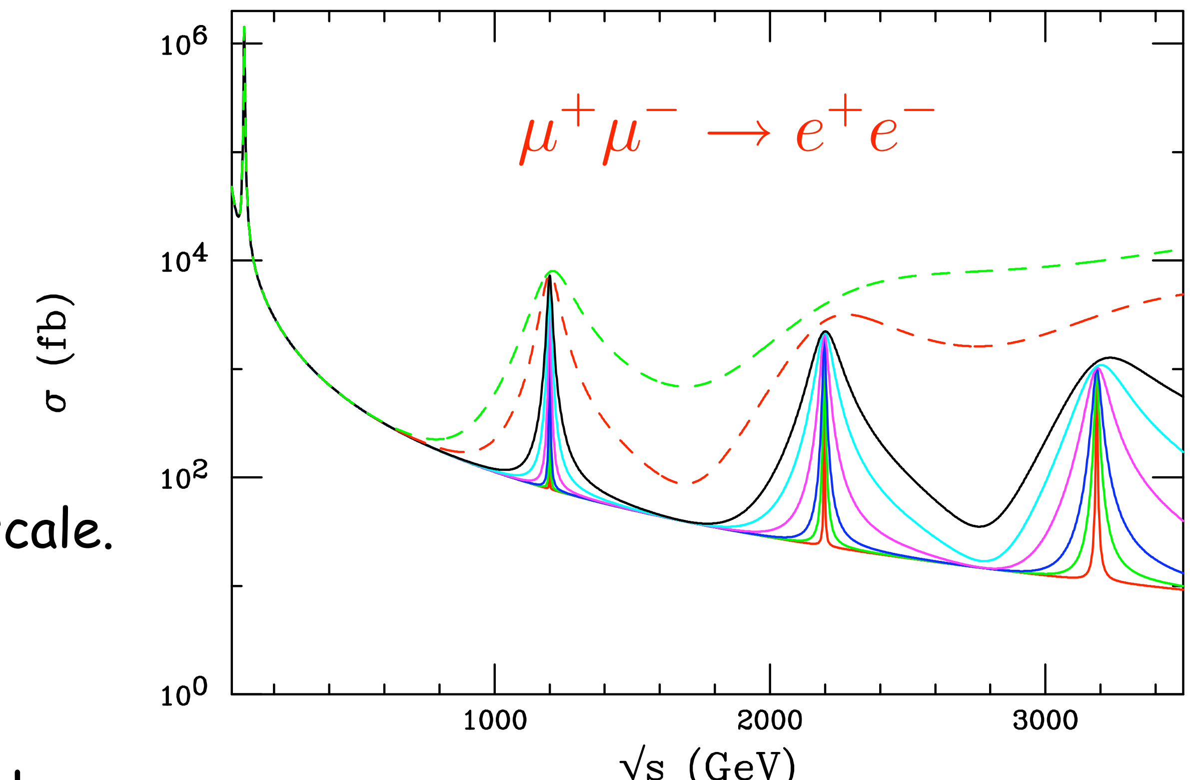


Extra Dimensions

Theoretical issues

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

possible KK modes



Randall-Sundrum model:
warped extra dimensions

- two parameters:
  - mass scale ∝ first KK mode;
  - width ∝ 5D curvature / effective 4D Planck scale.

LHC discovery - Detailed study at a muon collider

Summary

- A multiTeV lepton collider is likely required for full coverage of Terascale physics.
- The physics potential for a muon collider at $\sqrt{s}$ ~ 3 TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
- Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics. Sets the minimum luminosity scale.
- Proceed to a detailed study of physics case for 1.5-4.0 TeV muon collider:
  - Identify benchmark processes: pair production (slepton; new fermion), Z′ pole studies, h^0 plus missing energy, resolving nearby states (H^0-A^0; ρ_T-ω^0_T), ...
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity should be considered.
  - Estimates of collision point environment and detector parameters needed.
  - Must be able to withstand the real physics environment after ten years of running at the LHC.

Workshop on "Muon Collider Physics: Detectors and Backgrounds", Fermilab, Nov. 30-Dec. 2 (2009)